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Light measurement methods related to forage yield in a grazed northern conifer silvopasture in the Appalachian region of eastern USA

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Abstract

The Appalachian region is characterized by hilly topography and a humid temperate climate. In most areas agriculture is limited to pasture although the native climax vegetation is a species-diverse forest. Silvopasture systems can help diversify and increase farm income. Information is needed on the yield response of forage grown as an understory crop among trees. The light environment of a conifer silvopasture was characterized by three methods, a hand-held photosynthetically active radiation (PAR) meter for quick measurements over a large area, fixed PAR meters recorded using data loggers for a large number of measurements over time, and hemispherical photography with software to calculate seasonal direct beam radiation. Light data were considered in terms of forage yield. Plots were harvested when forage reached 20–25 cm in height after which the entire area was grazed by sheep. There were limitations to all methods of quantifying radiation environment for predicting yield. Yield decreased linearly with decreased PAR; however, data variability was high and correlations, while statistically significant, were weak. Grazed silvopastures are dynamic with shifting yield patterns in response to the interactions between the spatially variable soil, changing seasonal environment, and spatially variable animal impacts for each grazing event.

Introduction

The primary function of all plant biochemical processes is to facilitate the capture and storage of solar radiation energy in order to perpetuate the species. The minimal solar radiation intensity which allows plants to take up more energy than is expended for metabolic functioning is called the light compensation point. This point is highly temperature dependent with more light required to support respiration at higher temperatures (Levitt 1972). The relationship between compensation point and temperature is species dependent and related to the environment within which any species is best adapted.

Silvopastoral systems provide forages with an environment where both solar radiation and temperature vary spatially on daily and seasonal time scales. The way in which these parameters vary spatially depends on latitude, site aspect or exposure in hilly terrain, tree species and stand density, precipitation amounts and cloudiness. Our understanding of solar radiation impacts on understory yield has not kept pace with other research disciplines. For example, Sanchez (1995), emphasized soil–plant interactions as the specific biophysical components of agroforestry systems needing further research. In silvopasture research, solar input is frequently not measured and instead tree density and age is reported as a qualitative index of light environment expressed as shade (Lewis et al. 1983; Hawke and Wedderburn 1994; Clason 1995). The theory of how agroforestry systems partition solar radiation between trees and understory crops was presented as general principles (Reifsnyder 1989) but many of the assumed complex interactions are unresolved.

Forage growth does not have a simple relationship to light environment. Some C3 plants appear to use diffuse radiation more efficiently than direct beam radiation (Sinclair et al. 1992; Healey et al. 1998) so that in a humid, cloudy environment the amount of field-of-view open to reflective clouds is more critical than in sunny, arid regions. Light quantity and quality affects plant morphology and dry matter allocation (Belesky 2005) and carbohydrate partitioning (Deregibus et al. 1985; Frank and Hofmann 1994). As a result, far-red enriched light under tree canopies is likely to impact forage yield and nutritive value. Conifers potentially provide much less far-red enrichment compared to deciduous trees because they reflect and scatter much less far-red light (Gates 1980). Power et al. (2001) concluded that there was no difference in forage response as a result of deciduous or conifer overstory, however their study had only three tree species along with artificial shade cloth. Timing of daily exposure to solar radiation is also important since it affects plant carbohydrate content, thus energy value as animal feed (Ciavarella et al. 2000; Mayland et al. 2000)

Measuring the photosynthetically active radiation (PAR) component of solar radiation incident on forages is difficult for silvopastures relative to treeless pastures. There are trade-offs among the different methods in the spatial or temporal accuracy of measurements and large differences in resources required to collect and process light environment data. In a tropical agroforestry study, understory PAR values determined using a densiometer were preferred over calculations made from hemispherical photographs (Bellow and Nair 2003) while in a tropical forestry study it was concluded the reverse was true (Ferment et al. 2001). Earlier work by foresters suggested hemispherical photography was as reliable as various PAR measurement meters for determining PAR penetration through a forest canopy (Rich et al. 1993; Easter and Spies 1994). Small diameter sensors with weather stations or dataloggers are of limited value on a daily basis except for reference data at unshaded sites. These small sensors are more useful on a seasonal basis since the sun tracks over a range of forest canopy. Meter long PAR sensors can give improved spatial representation but are expensive in large numbers.

While direct beam solar radiation can be predicted using software to analyze hemispherical photographs of forest overstory, they cannot predict diffuse radiation except for clear sky conditions. Cloud type and location relative to gaps in the forest canopy have a dramatic effect on understory PAR, but this is a random and dynamic process. Midday incident PAR was twice as high under rows of black locust (*Robinia pseudoacacia* L.) when there was 30% cloud cover as under clear sky conditions (Feldhake 2001). Methods to measure diffuse PAR were developed using shadow bands (Grant 1997); however, diffuse radiation is not uniform spatially across the sky (Rosen et al. 1989), thus it is dependent on gap location within the tree canopy.

The primary hypothesis tested was that site yield in grazed, conifer silvopastures is highly correlated with midday PAR. Midday is the time of day with the least shading by trees and highest incident solar radiation levels. Also, in the Appalachian region, rainfall is generally plentiful and lime and fertilizer can be applied thus PAR is the limiting resource. A secondary objective of this work was to determine the relative value of different methods of spatially quantifying light environment for predicting yield.

Materials and methods

The research site is a 0.56 ha area of 35-year-old 17 m tall, mixed conifers on a farm site in southern West Virginia (37°47′ W latitude 81°00′ N longitude, 860 m elevation). The site is dominated by white pine (*Pinus strobus* L.) and red spruce (*Picea rubens* Sarg.) with a few scattered pitch pine (*P. rigida* Mill.) and short-leaf pine (*P. echinata* Mill.). The trees are growing on a Dekalb soil (fine sandy loam, mixed, mesic Typic Hapludult). Trees were planted on approximately 1.5 m centers, however, tree senescence over the years has left areas of the stand thinned and several large gaps occur, the largest of which is 10% of the total area.

The resulting area with a gradient of tree canopy closure was divided into 9×9 m blocks (69 total) with tree number (Figure 1) and basal area determined for each plot.

In mid-March 1999, 46 wether sheep (Ovis sp.) were fed baled, cool-season forage hay and shelled corn (*Zea mays* L.) scattered at random across the site to accelerate disruption of surface needle litter. The site was sown with a hand-operated cyclone seeder in April 1999 to 7.5 kg ha^{-1} 'Benchmark' orchardgrass (*Dactylis glomerata* L.), 3.8 kg ha^{-1} each of 'Elf' and 'Seville' perennial ryegrass (*Lolium perenne* L.), and 5.5 kg ha^{-1} 'Huia' white clover (*Trifolium repens* L.). Shelled corn was broadcast and sheep returned to the site to tread in the seed. Phosphorus was applied prior to grazing at rates adjusted to achieve a mean of 30 kg ha^{-1} Bray P in each block. The area was treated with 100 kg ha^{-1} K and 30 kg ha^{-1} N as a starter fertilizer. The site was grazed by sheep and reseeded in mid-August 1999.

On several anticipated clear-sky dates during 1999, PAR was measured during midday for all blocks using a 1 m Sunfleck Ceptometer PAR meter (Decagon Devices, Pullman, WA). Five equidistant measurements were recorded across the north–south center line of each block for the whole site followed by a second transect, collecting

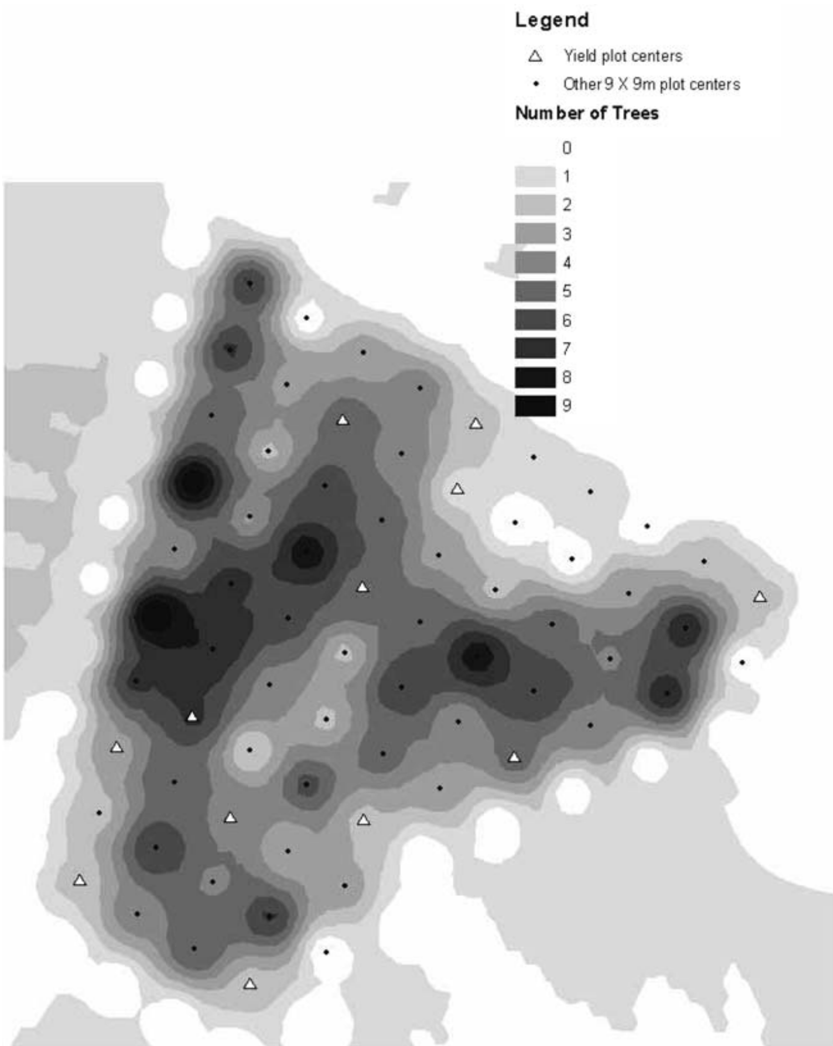

Figure 1. Tree density of 9×9 m plots in the conifer silvopasture in the central Appalachian region of eastern USA. Figure was generated using ArcGIS 8.2 Spatial Analysts and the inverse distance weighting option.

five additional measurements along the east–west center line of each block for the whole site. Periodically a PAR measurement was made 50 m outside of the conifer stand in an open field. About 2 h were required to complete measurements on a given day. Based on these data, 12 blocks with a range of midday PAR levels were chosen for harvesting with four yield strips located in each, one in each quadrant. Four blocks were chosen with mean PAR of about 20, 50, and 80% of maximum solar radiation, respectively, based on the average of measurements from three dates.

Plot harvest began in mid April 2000 when average canopy height of accumulated herbage reached 20 cm. Yield was determined from four, 0.1-m^2 areas clipped to a 4 cm residue. Harvest strips were selected to avoid rocks and dead tree stumps. Subsequent harvests during 2000, 2001, and 2002 occurred whenever average canopy height reached 20–25 cm. Immediately after each harvest the entire area was grazed by sheep to a target residue height of 5 cm. It usually took two or three days for animals to complete grazing to the mean target residue height.

During July 2001, on an overcast day, upward hemispherical images were photographed in the center of each yield block using a Nikon Coolpix 950 digital camera with a Nikon FC-E8 Fisheye Converter and a self-leveling mount. Images were analyzed for transmitted solar radiation through the tree canopy as a function of day-of-year (DOY) using WinSCANOPY software (Regent Instruments Inc., Quebec, Canada).

During 2002, continuous daily PAR was measured immediately after harvesting, over the exact spot clipped, using LI-COR Line Quantum Sensors (LI-COR Lincoln, NE). All four harvest sites within four blocks representing the different light environments were measured every 10 s and averaged into 5 min increments using Campbell 21X dataloggers (Campbell Scientific Inc., Logan, UT).

Soil moisture in the top 15 cm was measured each week for all harvest sites using TRIME-FM TDR probes (MESA Systems Co., Medfield, MA). Light quality, in terms of red/far-red ratio, was determined using a LI-COR LI-1800 Spectroradiometer fitted with a fiber optic cable and telescopic lens targeted at a Labsphere (North Sutton, NH) white body reflectance standard from a distance allowing measurement of a 20 cm diameter surface area. Measurements were made at sites with a gradation of shading, near noon, under clear sky conditions. Correlations (Pearson's) and regression statistics were used to evaluate how yield and light measurement systems data were related.

Results and discussion

Yield data for the first growing season were not highly correlated with midday PAR representing 20, 50, or 80% of maximum as measured with the Decagon PAR meter and averaged for three light environment measurement dates. The r^2 for regressions predicting yield as a function of Decagon PAR meter data ranged from 0.07 to 0.3 for the six harvests in 2000 with an r^2 of 0.25 for the entire season (Table 1). Yield and PAR were more highly correlated in 2001 and 2002 with r^2 values of 0.38 and 0.44, respectively.

Closer scrutiny of PAR data revealed some cloud formation occurred before the end of the two hour measurement period on two days from which data was used to group plots, leaving only one day when no cloud-induced errors occurred. When regression equations were calculated using PAR from this date only, and using actual PAR rather than cluster values, the r^2 for 2000 nearly doubled to 0.48 with modest increases for 2001 and 2002 (Table 1). A hand-held PAR meter is useful for collecting data quickly over relatively large areas, however, in the humid Appalachian region there are very few days when data are not compromised by cloudiness, therefore, it is difficult to obtain representative data for a broad range of solar angles across the growing season.

In 2001, digital photographs of the sky, made using a hemispheric lens, were taken from the center of each yield block. Maximum potential direct beam solar radiation was calculated from sun path diagrams superimposed over whole-sky images. Values calculated for a week prior to harvests were used for regression analysis. These values were more highly correlated with yield for 2001 and 2002 than Decagon PAR meter data but not for 2000 (Table 1). Digital hemispheric photographs are useful for documenting PAR changes throughout the growing season as a function of sun angle. Two main limitations are the inability to predict the diffuse PAR component, which is important in cloudy regions, and that each

Table 1. Values of r^2 for yield as a function of PAR measured with a Decagon meter and clustered into 20, 50, or 80% of maximum, of actual PAR measured with a Decagon meter and of maximum direct beam solar radiation and % open sky determined with hemispherical photography and WinSCANOPY software in the central Appalachian region of eastern USA.

Harvest	r^2			
	Decagon		WinSCANOPY	
	20, 50, 80%	Actual	Direct beam	% Open sky
2000				
1st	0.26	0.48	0.09	0.09
2nd	0.24	0.43	0.27	0.09
3rd	0.28	0.49	0.01	0.04
4th	0.30	0.50	0.02	0.05
5th	0.24	0.35	0.25	0.00
6th	0.07	0.07	0.00	0.07
Total	0.25	0.48	0.19	0.00
2001				
1st	0.48	0.57	0.46	0.06
2nd	0.45	0.56	0.29	0.31
3rd	0.29	0.26	0.70	0.13
4th	0.03	0.03	0.30	0.00
5th	0.14	0.10	0.22	0.04
Total	0.38	0.41	0.70	0.06
2002				
1st	0.33	0.47	0.18	0.01
2nd	0.55	0.55	0.47	0.17
3rd	0.17	0.26	0.32	0.08
4th	0.47	0.43	0.11	0.02
Total	0.44	0.52	0.59	0.06

photograph allows prediction of direct beam PAR viewed from a camera lens only 1.5 cm in diameter. Values of PAR may vary considerable over short distances depending on the amount and size of gaps in the forest canopy.

A close examination of the yield blocks revealed that an overhead branch obscured PAR more for the center of the block than the actual harvest sites, 2 m from the center in each direction, for two of the blocks. If data from these two blocks are eliminated from the regression analysis, the ability to predict yield from direct beam PAR is substantially improved giving seasonal total r^2 values of 0.41, 0.82 and 0.83 for 2000, 2001, and 2002, respectively. Had several more photographs been taken within each block this source of error could have been minimized. Photographs would also be of much greater use for silvopastures with a known geometry to the tree placement than for a site such as this where tree location is essentially random within blocks.

Field-of-view not obscured by tree canopy was also calculated, using WinSCANOPY software, as a relative index of diffuse radiation received by each plot. These values ranged from 19 to 38% across the study area. There was poor correlation between open sky field-of-view and yield for individual harvest or for yearly harvest totals (Table 1).

The variability, exhibited in Table 1, in how well yield correlated to the different PAR characterizations for individual sites points to how misleading any individual measurement date could potentially be in describing a site. There was some uncertainty in how closely PAR characterizations were linked both spatially and temporally to exact harvest strips.

During 2002, LI-COR line quantum sensors were used to measure PAR over the exact harvest strip immediately after clipping. One sensor was placed over each selected harvest strip, enabling us to measure the total of direct and diffuse PAR at the exact harvest spot. After the first harvest, the weather was quite variable. The PAR on a very cloudy day was not correlated with yield (Table 2). The PAR on a mostly sunny day predicted yield better than PAR on a cloud-free day. This is not surprising since cloud-free days are unusual and mostly-sunny days represent the best growing condition because light scattering from clouds increases diffuse radiation for regions receiving little direct beam radiation.

The amount of open sky over the 12 harvest blocks averaged 28%. However, direct beam solar radiation calculated using WinSCANOPY software averaged 42%. The difference is due to sunlight penetration being greatest near solar noon when canopy interception length is least and solar radiation highest. Direct beam radiation day length under the tree canopy was effectively 2 h shorter both early and late in the day compared to over the tree canopy (Figure 2). Average PAR measured with the hand-held Decagon meter was greater yet at 49% since this was only measured at midday and was not affected by early- and late-day shading.

Total annual yield was highly variable between blocks and to a lesser degree between years (Table 3). On the higher yielding sites, dry matter production was comparable to orchardgrass-dominated clipped (Belesky and Fedders 1994) or

Table 2. Values of r^2 for yield as a function of PAR measured with LI-COR line quantum sensors for three 2002 harvests in the central Appalachian region of eastern USA.

Harvest	r^2
1st Very cloudy	0.04
1st Mostly sunny	0.54
1st Very sunny	0.46
2nd Mostly suuny	0.64
3rd Mostly sunny	0.46

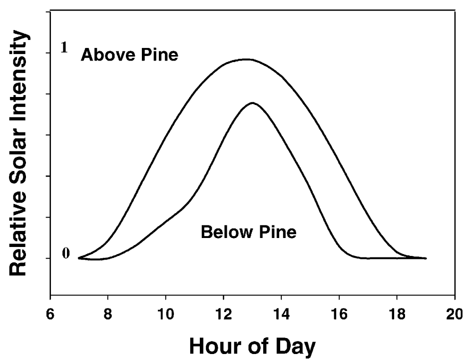

Figure 2. Relative solar radiation calculated for over tree canopies (top line) and the average for the seven harvest sites, not on the field edge, using WinSCANOPY software and hemispherical photos in the central Appalachian region of eastern USA. All values are normalized relative to peak daily values above the pine.

grazed (Carlassare and Karsten 2003) traditional pasture, and silvopastoral (Burner 2003) conditions. Soil depth varied twofold between sites and volumetric soil moisture depletion varied by 45% during late summer drought occurring in 2002.

Correlation of seasonal block yields between years was highly significant (Table 4) indicating all factors combined (microclimate, soil, animal behavior) produced some consistency in how blocks yielded. The number of trees and basal area were correlated with yield in 2002, when very dry conditions occurred in late summer. Soil depth and moisture depletion potential were not correlated with yield for any of the 3 years. The WinSCANOPY and Decagon meter methods of assessing incoming radiation were correlated with each other but with yield only some years. The correlation between different methods of site PAR characterization was similar to those found for different measurement systems by Ferment et al. (2001) but not as good as found by Bellow and Nair (2003). Only the Decagon PAR meter method of assessing incoming radiation was correlated with tree number and basal area which is expected since those measurements were made midday and were not influenced by early and late day shading from trees in neighboring blocks.

There was a highly significant correlation between total seasonal yield and both PAR measured with the Decagon meter and solar radiation calculated using WinSCANOPY when normalized (each site yield divided by maximum yield) to combine the 3 years of data (Figures 3 and 4). There was however, a large amount of variability

Table 3. Descriptive and yield data for twelve yield blocks within the conifer silvopasture in the central Appalachian region of eastern USA.

Site	OPN (%)	WIN (%)	DEC (%)	SLD (m)	MST (%)	TRN	TRA (m^2)	YD0 (kg ha^{-1})	YD1 (kg ha^{-1})	YD2 (kg ha^{-1})
1e	32	31	83	0.39	20.7	2	0.13	5310	4810	4000
1j	36	73	97	0.44	24.3	2	0.22	2880	3980	3760
2c	27	40	21	0.93	21.2	5	0.27	6130	6690	3880
3e	32	76	84	0.63	19.9	1	0.08	7320	9150	7950
4d	21	36	20	0.53	16.8	5	0.24	4140	5160	3730
5g	26	31	24	0.60	18.1	5	0.44	4490	4470	3300
7b	19	48	34	0.83	22.0	7	0.25	2910	4350	3390
7e	22	25	73	0.67	20.7	2	0.13	6420	6250	5440
8a	33	26	18	0.56	23.3	3	0.27	2870	3590	2440
8c	22	22	47	0.59	21.7	4	0.14	4800	4270	3200
10a	31	27	12	0.84	23.8	2	0.18	3010	3610	3550
10d	38	65	78	0.69	24.4	2	0.15	5330	8610	5560

Notes: OPN = percent open sky calculated with WinSCANOPY software; WIN = summer potential direct beam radiation calculated with WinSCANOPY software; DEC = midday PAR measured with a Decagon 1 m PAR meter; SLD = soil depth; MST = soil moisture depletion during the driest period; TRN = number of trees; TRA = tree basal area at 1.5 m; YD0 = total seasonal yield for 2000; YD1 = total seasonal yield for 2001; YD2 = total seasonal yield for 2002.

Table 4. Pearson's correlation coefficients for yield and block description data for the conifer silvopasture in the central Appalachian region of eastern USA.

	YDO	YD1	YD2	WIN	DEC	TRA	TRN	SLD
YD1	0.82**							
YD2	0.77**	0.89**						
WIN	0.17	0.57*	0.61*					
DEC	0.40	0.45	0.60*	0.61*				
TRA	−0.44	−0.44	−0.60*	−0.24	−0.60*			
TRN	−0.33	−0.34	−0.55*	−0.30	−0.62*	0.64*		
SLD	0.08	0.20	0.05	0.07	0.50	0.10	0.36	
MST	−0.36	−0.10	−0.10	0.25	0.24	−0.29	−0.36	0.18

Notes: YD0 = total seasonal yield for 2000; YD1 = total seasonal yield for 2001; YD2 = total seasonal yield for 2002; WIN = summer potential direct beam radiation calculated from WinScanopy software; DEC = midday PAR measured with a Decagon 1 m PAR meter; TRA = tree basal area at 1.5 m; TRN = number of trees; SLD = soil depth; MST = soil moisture depletion during the driest period.
*Significant at $p < 0.05$.
**Significant at $p < 0.01$.

due to the less than perfect temporal characterization of site PAR with the Decagon meter and the less than perfect spatial characterization of solar radiation with the WinSCANOPY software and hemispheric images. Other factors such as tree position in adjacent blocks varied across the site and influenced forage productivity. One site in particular had very high incident solar radiation but surprisingly low forage production all 3 years.

Even with actual harvest strip, full-day PAR measurements using the LI-COR quantum sensors over each harvest strip of a four-block subset, there was a high degree of variability. The total-day integration of PAR was more highly correlated with yield than the 2 h midday integration (Figures 5 and 6) which should approximate the relative values obtained with the Decagon PAR meter. Relative yield did not decrease as rapidly as relative PAR for all sites and there appeared to be a linear trend. In the 20–30% total-day relative PAR range there was still over 40% relative yield for some yield strips. This seems remarkable since solar radiation in this area is already attenuated by roughly half due to cloud cover. In a very sunny climate useful forage production seems feasible under tree canopies shading over 80% of incident solar radiation.

Spatial regions within a silvopasture that differ in PAR reception also provide environments that differ in light quality. The red/far-red ratio of incident radiation influences forage morphology and carbohydrate partitioning (Deregibus et al. 1985; Frank and Hofmann 1994). In silvopastoral systems, regions receiving little direct PAR have a lower red/far-red ratio than regions receiving con-

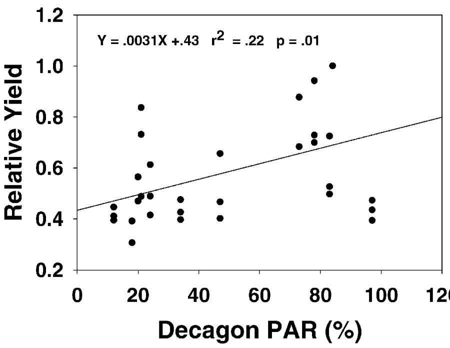

Figure 3. Seasonal relative yield for 2000, 2001, and 2002 as a function of midday PAR for each harvest block measured with the Decagon PAR meter divided by PAR measured in an open field in the central Appalachian region of eastern USA.

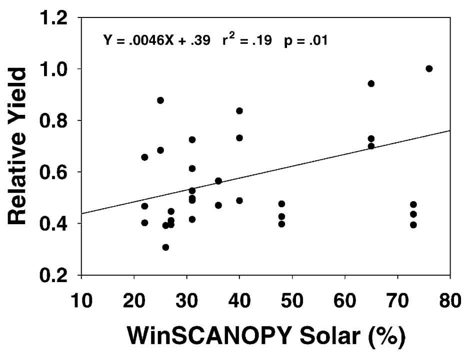

Figure 4. Seasonal relative yield for 2000, 2001, and 2002 as a function of total daily potential direct beam solar radiation for each block divided by total direct beam solar radiation over tree tops calculated using WinSCANOPY software in the central Appalachian region of eastern USA.

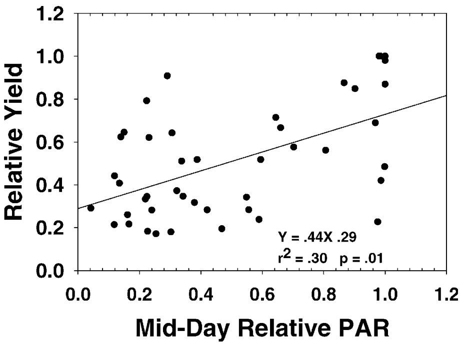

Figure 5. Relative yield for each harvest in 2002 for harvest blocks instrumented with LI-COR line quantum sensors as a function of measured PAR from 11:00 to 13:00 divided by PAR for an unshaded site in the central Appalachian region of eastern USA.

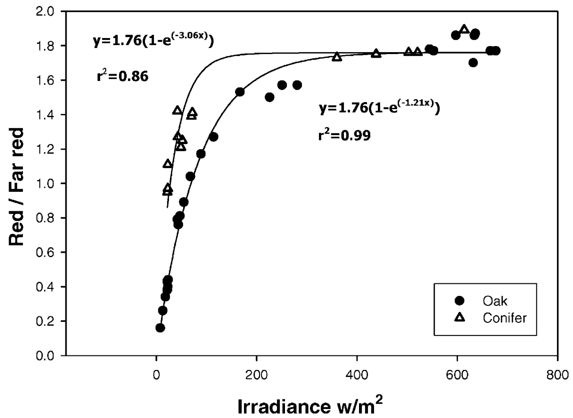

Figure 7. Red/Far-red light quality as a function of full sun midday irradiance within a conifer and a oak silvopasture in the central Appalachian region of eastern USA.

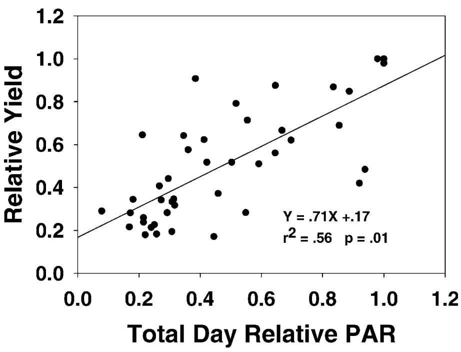

Figure 6. Relative yield for each harvest in 2002 for harvest blocks instrumented with LI-COR line quantum sensors as a function of total daily measured PAR divided by total daily measured PAR at the site receiving the maximum amount in the central Appalachian region of eastern USA.

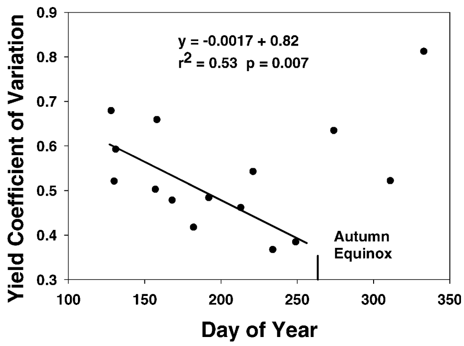

Figure 8. Yield coefficient of variation as a function of Julian day for harvests from 2000, 2001 and 2002 in the central Appalachian region of eastern USA. Each point is calculated from the mean and standard deviation of all 48 harvest strips across the site.

siderable full solar radiation (Figure 7). Light quality is however not static, it shifts along this curve as the sun and clouds move relative to tree canopies. It is interesting to note that at low solar radiation levels the red/far-red ratio is considerably higher for conifer silvopastures than deciduous silvopastures. It is not known if this difference has management or economic consequences.

One factor that may have decreased the correlation between PAR and yield is that grazing may have changed the forage in ways that clipping would not. Forages in high PAR environments have higher total non-structural carbohydrates than in low PAR environments which translates to higher palatability (Ciavarella et al. 2000; Mayland et al. 2000), thus greater grazing pressure. All 3 years, the yield coefficient of variation decreased across the site between early spring and autumn equinox (Figure 8). This is predicted when both grazing and vegetation respond to the same patterning agent, in this case PAR (Adler et al. 2001).

Conclusions

The random arrangement of trees within this grazed silvopasture made it difficult to effectively quantify PAR both spatially and temporally. All three methods of measuring the light environment within this silvopasture were highly correlated with seasonal yield but the variability in individual harvests was very high. In general, total daily PAR was higher than would be predicted from the amount of open sky in the field-of-view since the least amount of sky-obscuring tree vegetation is generally near perpendicular to the horizontal plane where the sun is during midday and solar intensity is greatest. Yield was influenced not only by PAR, but varied from harvest to harvest due to other environmental, site, and grazing-induced conditions. On the average, total yield was linear in the range of 30–80% of maximum PAR. There were instances where yield was over 60% of the highest PAR site for sites receiving less than 40% as much PAR. Many of the sites with less than 40% of maximum PAR however, had less than 30% of the maximum yield. The greatest consistency in yields over 50% of maximum were for PAR levels over 40% of maximum.

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